LIFE CYCLE GHG EMISSIONS OF MATERIAL USE IN THE LIVING LABORATORY

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Abstract

This paper presents an analysis of the implication design choices have on embodied material emissions, with a view to better understand how the life cycle assessment of buildings can be better integrated into the building design process. The analysis is applied to a pilot net zero emission building (nZEB) called the Living Laboratory, which has been developed by the Norwegian Research Centre on Zero Emission Buildings. The impact of embodied emissions is presented through a series of sensitivity analyses that consider the definition of a functional unit and system boundary. The results for embodied emissions are presented for each building component, and highlight important design drivers for the reduction of emissions in building construction.

Compared to the previous ZEB projects, the total embodied emission result from the Living Laboratory of 23.5kgCO_{2eq}/m^2/yr is considered high. This is due to the building having a more comprehensive material inventory, which includes more life cycle phases, and uses a higher level of technical equipment and state-of-the-art materials.

The results show that the outer roof, photovoltaic system and outer walls drive the highest emissions. Further analysis revealed that in some cases high emissions came from the production phase, whereas in other cases it originated from the replacement phase. The results show that timber, electrical components and metal were responsible for driving the highest emissions. The results show that certain design choices, such as a change in foundation design, can reduce embodied emissions by 21%, which could be further reduced if low carbon concrete was used.

Keywords: *net zero emission buildings, embodied emissions, design drivers, design process*

1 Introduction

1.1 Background

Previously, the Research Centre on Zero Emission Buildings (ZEB) carried out two simplified concept studies in autumn 2011, with the goal of achieving a ZEB-OM ambition level. In the beginning of 2012, it was decided to develop these concepts into more realistic building models; one of the concept studies was an office building, (Dokka et al., 2013) whilst the other was a single-family house. (Houlihan Wiberg et al., 2013) The two ZEB concepts were designed to ‘provide a benchmark for Nordic conditions (i.e. cold climate) and [as] a starting point for comparison’ of embodied emissions. (Georges et al., 2015) The Living Laboratory is one of the first net ZEB pilot studies to be built and tested. This report builds upon the embodied emission methodology developed by the ZEB centre, and applies it to the real case of the Living Lab; with a view to better understand the implication of design choices on embodied material emissions. The Living Lab is an experimental facility that uses state-of-the-art materials and technical equipment. It will be tested and occupied by researchers, students and professors from the Norwegian University of Science and Technology (NTNU).

2 Building Description

The Living Laboratory is a single storey, temporary, multi-purpose demonstration and experimental facility. The building is of a detached, single-family house typology, which represents over 52% of the Norwegian building stock. (SSB, 2013) The building is located on NTNU's Gløshaugen campus, Trondheim, Norway. A photograph and section of the building can be seen in Figure 1. A comprehensive explanation of the building envelope, services and energy supply system can be found in Inman and Houlihan Wiberg, 2015.

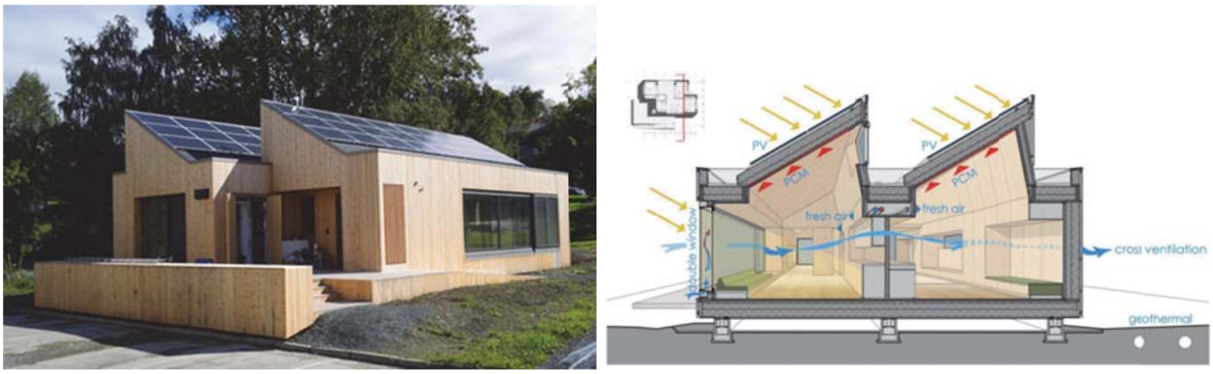

Fig. 1 *Photo and Section of the Living Lab (Finocchiaro et al., 2014)*

2.1 Building Envelope

The building is comprised of a timber-framed loadbearing structure, with a raised timber floor construction, mineral wool insulation and parquet timber flooring. The building envelope consists of a timber framed construction, mineral wool insulation, timber cladding, whilst the roof comprises of the same construction with additional integrated phase change material (PCM) and in-roof building adapted photovoltaic panels (BAPV). The north and south windows comprise of triple-glazed units with double-skin insulated aluminium frames. The east and west doors comprise of aluminium-clad timber-framed triple-glazed units with integrated vacuum insulated panels (VIP).

The building consists of two adjoining rectangular cells approximately 12.5 x 4.1 metres, with elongated facades facing north and south. The Living Lab contains two bedrooms, one bathroom, a living area, a kitchen, a study, as well as an entrance hallway and technical room.

The ground floor has a heated floor area (BRA) of 102 m^2, a gross floor area (BTA) of 132 m^2, a net floor area (NTA) of 97 m^2 and a built up area (BYA) of 219 m^2. The choice of definition of area plays an important role in the sensitivity of the functional unit which is explained in more detailed in Inman and Houlihan Wiberg, 2015. The total window and door areas are 47.3 m^2, which gives a window/door to floor area ratio of 46.4%.

2.2 Building Services

The building services category includes sanitary installations, heating, ventilation and air conditioning, as well as lighting and common household appliances. It should be remembered that, in order to simulate multiple energy scenarios, the technical systems for the Living Laboratory have purposefully been over specified. Any additional technical equipment, control systems, sensors or probes used to document the performance of the Living Lab, have been purposefully left out of the material inventory.

2.3 Energy Supply System

The energy supply solution for heating, cooling and electricity is an 'all electric' solution based on: 1) High-efficiency PV on the roof, 2) solar thermal collectors on the south façade, 3) geothermal heat pump. An explanation of the passive and active design strategies used, to optimise the design of the Living Lab, can be found in Inman and Houlihan Wiberg, 2015.

3 Method

3.1 Goal and Scope

The goal of these calculations is to estimate, and thus provide an overview of the materials and components in the Living Laboratory, which contribute the most to embodied CO_{2eq} emissions. The calculations are based on the principals of environmental assessment through life cycle assessment, according to ISO 14044: 2006. The functional unit is set to 'emissions per $1m^2$ of heated floor area (BRA) per year of operational building lifetime', so that the results are comparable with the other ZEB pilot projects. The results are normalised according to a BRA of $102m^2$ and a building lifetime of 60 years. For transparency, a sensitivity analysis of the functional unit, in terms of definition of area and building lifetime, shall be presented.

3.2 System Boundary and Material Inventory

The material inventory was calculated manually using the architect's drawings, and has been cross-referenced with product literature and on-site observations. The system boundary is defined according to NS-EN 15978: 2011 and is limited to the extraction of raw materials and the manufacture of products and materials (A1–A3), the transport of goods to site (A4) and their installation into the building (A5). Replacement of new materials over the lifetime of the building is also included (B4), including the transportation of these new materials to site (A4).

Full details on what is included in the system boundary and material inventory can be found in Inman and Houlihan Wiberg, 2015; as well as information on the reference service lifetimes (RSL) for the different materials and component, which are based on manufacturer's literature, BKS 700.320 and 700.330, Ecoinvent reports and previous ZEB pilot projects. An assumption has been made, that the PV panels will be produced 50% better in 30 years' time.

3.3 Calculation Method

Generic life cycle inventory data has been accessed from SimaPro Analyst version 8.0.5, and uses datasets from Ecoinvent version 3.1. (PRé, 2015) (Ecoinvent Centre, 2014) All the calculations have been structured in MS Excel according to NS 3451: 2009 Table of Building Elements. (NS3451, 2009) The IPCC GWP 100 year scenario method has been used, for the impact assessment of the material inventory. (PRé, 2007) The choice of electricity mix used in the production of materials is based on those specified in the Ecoinvent database. For example, the concrete dataset used in the analysis, is based on a concrete process from Switzerland, using the Swiss electricity mix as an input. The photovoltaic modules use a rest of world (ROW) electricity mix factor, since they are produced in Singapore.

4 Results

4.1 Total Embodied Emission Results

The results show that the total embodied emissions are calculated as 23.5kgCO_{2eq}/m^2/yr, see Table 1. The majority of emissions come from the production (50%) and replacement (40%) phases. Transport to site and construction emissions account for 5% each.

Tab. 1 *Table 1 Carbon dioxide $_{(eq)}$ emissions from material use in the Living Laboratory*

Life Cycle Stage	kgCO_{2eq}	kgCO_{2eq}/yr	kgCO_{2eq}/m^2 60 years	kgCO_{2eq}/m^2/yr
Initial Materials (A1–A3)	74,121	1,235	727	12.1
Transport to Site (A4)	6,188	103	61	1.0
Construction (A5)	7,412	124	72	1.2
Replacement (B4)	56,067	934	550	9.2
TOTAL	**143,788**	**2,396**	**1,410**	**23.5**

When compared to other ZEB projects such as the ZEB single-family house (SFH), the total embodied emissions from the Living Laboratory are considered high. For the same system boundary (A1-3, B4), it can be seen that the Living Lab (21.3kgCO_{2eq}/m^2/yr) has three times higher emissions than the SFH (7.2kgCO_{2eq}/m^2/yr). During the 60 year lifetime of the two buildings, it can be seen that the Living Lab (130,188kgCO_{2eq}) has double the amount of total emissions than the SFH (69,139kgCO_{2eq}).These higher emissions from the Living Lab can be explained by the fact it has a more detailed material inventory, and a more comprehensive system boundary than the ZEB SFH. Both of these factors contribute to higher total embodied emissions. In addition, the Living Lab has an area of 102m^2, whilst the ZEB SFH has an area of 160m^2 which means that the Living Lab has a higher concentration of material and emissions per m^2 of BRA than the SFH.

The results show that the majority of total emissions (65%) originate from the building envelope, whilst one quarter comes from the PV in the outer roof. The remaining 12% of emissions come from ‘heating, ventilation and sanitation’ of which appliances account for 8%.

The definition of area plays an important role in the sensitivity of the functional unit, resulting in a two-fold variation in total embodied emissions. The results show that choosing a gross floor area (BTA) scenario results in 18.2kgCO_{2eq}/m^2/yr compared to 23.5kgCO_{2eq}/m^2/yr in the heated floor area (BRA) scenario. If a net build up area (BYA) definition is used, emissions are almost halved to 10.9kgCO_{2eq}/m^2/yr, and conversely increased to 24.7kgCO_{2eq}/m^2/yr in the net built up area (NTA) scenario.

The functional unit is also sensitive to the definition of building lifetime. Given that the Living Lab is a temporary building, it is likely that the building lifetime will be shorter than the standard 60-year lifetime specified. For that reason, a sensitivity analysis of the results, in relation to the length of building lifetime has been calculated. Even though this is a theoretical exercise, the results show more than a 74% decrease in emissions relative to a doubling of building lifetime, from 30 to 60 years. When this lifetime is extended to 75 years, the decrease in emissions is 71%, and 65% when increased to 100 years.

In terms of replacement, the SFH has 1.95kgCO_{2eq}/m^2/yr, whilst the Living Lab has 9.2kgCO_{2eq}/m^2/yr. This difference is explained by the fact that less than 30% of the materials used in the SFH were replaced during the lifetime of the building, compared to over 40% in the Living Lab which is explained by the fact that all replaced materials in the Living Lab include transport and construction emissions.

4.2 Building Envelope Results

The majority (almost one quarter) of emissions arise from the outer roof because of the complex roof form, aluminium flashings, roof lights and over-dimensioned PV mounting frame. The PV is the next highest driver, contributing just over one fifth of total emissions, followed by the outer walls with 15% of emissions. Appliances contribute 8.2%, followed by the 'Groundwork and Foundations' (4.5%) and 'Floor Structure' (3.3%). An interesting design driver for reduced emissions was the decision to omit the concrete footing from the strip foundation, which resulted in almost half the quantity of concrete being used (16m^3 to 9m^3) and a 20% reduction in embodied emissions from concrete.

Timber contributes to almost one fifth of emissions, because the building is predominantly of timber construction. Similarly some of the wood products have been processed (e.g. plywood processing involves glue additives) which may lead to an increase in embodied emissions compared to unprocessed timber products.

4.3 Building Services Results

The emissions from appliances account for 8% of total emissions in the building. The replacement emissions originate from the replacement of white goods, which have a product service lifetime of between 10-15 years, and therefore have to be replaced 4 to 6 times during the lifetime of the building. The washing machine accounts for driving the highest emissions (33%), followed by the dishwasher (20 %), oven (19%), fridge freezer (15%), tumble dryer (10%) and hob (4%).

Both the sanitary, lighting and electrical categories contributed negligible emissions to total embodied emissions. These categories experience low emissions because at the time in which calculations were carried out, a complete material inventory was not available for these items. The heating system contributes only 3% to total emissions. The solar thermal collectors have an RSL of 25 years and are replaced 2.4 times, whilst the hot water tank and heat pump have an RSL of 20 years and are replaced 3 times. The heat pump accounts for driving the highest emissions (31%) in this component, followed by the solar thermal collectors (26.7%), hot water tank (20%), PEX pipes (12.3%) and heat emission plates (10.1%).

The ventilation and air-conditioning category is also responsible for negligible emissions. There are no replacement emissions due to the 60 year RSL. The steel ventilation ducts are responsible for driving the highest emissions (43.6%) in this component, followed by the combi-exhaust (35.8%), supply grill (10.2%), air handling unit (5.5%), combi-intake (3%), extractor fan (1.1%) and flexible duct (0.75%).

4.4 Energy Supply System Results

The ‘other electric’ power category is responsible for 23% of total emissions in the building. The PV balance of systems (BOS) accounts for 68% of the replacement emissions, of which the inverters account for 91% of these emissions. The PV replacement emissions account for over one third of emissions. The product service lifetime for PV is 30 years, so they are replaced twice during the lifetime of the building. However, it has been assumed that the panels will be produced 50% better in 30 years' time, with half the amount of material emissions per m^2. In contrast, the inverters have a 15-year RSL, and are replaced four times.

The ZEB emission factor for electricity has been used (0.136kgCO_{2eq}/kWh), to calculate a PV cumulative energy yield of approximately 8996 kWh/m^2/yr over a 60-year lifetime per m^2 of module. (Graabak and Feilberg, 2011) (Kristjansdottir et al., Submitted) On-site PV energy production counterbalances 94,054kgCO_{2eq} of 143,788kgCO_{2eq} emissions, which equates to 65% of total embodied material emissions. In order to compensate for all emissions relating to material use, a total of 121m^2 PV is required, meaning that an additional 42m^2 of PV would need to be installed on-site (this does not account for the additional material emissions from the installation of additional PV modules and supporting services).

5 Discussion and Conclusion

This report has documented the design and construction of the Living Laboratory in terms of its embodied material emissions. Compared to previous ZEB projects, the results show relatively high embodied emissions, with total emissions of 1410kgCO_{2eq}/m^2 over a 60-year lifetime and 23.5kgCO_{2eq}/m^2/yr. There are multiple reasons for this. Firstly, a more comprehensive material inventory was available for the Living Lab as an 'as built' project. In addition, the system boundary includes more life cycle stages. Furthermore, since this is a ZEB demonstration building, it has higher emissions than a normal building of its size, since a high level of technical equipment and state-of-the-art materials are used.

The key components which drove the highest emissions were found to be in the building envelope (65%). Other key drivers were found in the PV modules (22.7%), and appliances (8.2%). It was interesting to note that the VIP, which is typically identified as a high driver of emissions, was found to be responsible for only 2.2% of emissions, which is largely due to the small quantity used sensitively in the design. The results show that state-of-the-art materials, such as VIP and PCM, may be used sensitively and effectively without contributing significantly to embodied material emissions.

A significant finding was found in the choice of a three-strip foundation design, which reduced emissions by almost one third, compared to the raft foundation design used in the single-family house (SFH). As a result, the Living Lab has used half (16m^3) the volume of concrete compared to the SFH (32m^3). The findings also show that omitting a concrete footing from the foundation, between the design and construction phase, has led to over a 40% reduction in the amount of concrete used (9m^3), and a 20% reduction in emissions. This could be further reduced if low carbon concrete was used.

The findings show that components with a high proportion of materials with long RSLs, e.g. 60 years, experience the majority of emissions during the production (50%) phase, whereas components with materials with short RSLs, e.g. 15-20 years, typically have a higher proportion of emissions originating from the replacement (40%) phase. Transport to site and construction emissions account for 5% each.

In the outer roof, the majority of emissions came from the production phase (57%) compared to the replacement phase (34.3%), whereby the complex roof form together with the PV mounting frame and flashings drove higher embodied emissions. In contrast, the appliances have one third less (20%) total emissions from the production phase, and 40% higher emissions (80%) from the replacement phase. This is due to the RSL of appliances being 10-15 years, compared to the 60-year lifetime of the building.

The PV emission balance highlights that further measures are required to reduce the amount of emissions relating to material use, and to improve the efficiency of energy production from photovoltaic panels or other renewable sources on-site. Given that the outer roof, PV modules and mounting frame contribute almost half to total embodied emissions, further work could investigate building integrated, instead of building adapted PV, and a less elaborate roof form, which may save on material emissions, simply because less material is used. Further work could include comparing these two types of systems with a non-integrated PV solution that uses a less-complicated flat roof construction. It would be interesting to see how much extra energy could be produced on-site if a one-sloped roof design was implemented, with no overshadowing. The material emission balance highlights that further measures are required, to reduce the amount of emissions relating to material use, and to improve the efficiency of energy production from photovoltaic panels or other renewable sources on-site.

The functional unit sensitivity analysis raises the question of whether or not a 60-year lifetime is appropriate for the Living Lab, since the building is temporary, and will be dismantled at its end-of-life (EOL). In these circumstances, there should be more focus on the demountability and recyclability of the building, rather than the durability of materials. The results also show that the definition of area plays an important role in the sensitivity of the functional unit, resulting in a two-fold variation in total embodied emissions.

In conclusion, it was found that material optimisation should be considered at an early stage in the design process, in order to reduce embodied material emissions. These results provide useful approximations for embodied material emissions, for use by designers during the early design phase, when a detailed material inventory may not necessarily be available. It also highlights methodological and design considerations when carrying out a life cycle assessment of a building. Furthermore, the Living Lab provides alternative solutions for low embodied emission design.

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